Key considerations for reopening schools during the COVID-19 pandemic

Version 2.0 – Updated 12.18.20

Executive Summary

School closures deprive students of critical opportunities for in-person learning and exacerbate societal inequities, but reopening schools during the COVID-19 pandemic is challenging in the face of limited information and conflicting public health advice.

To better understand the risks associated with returning to in-person learning, we use an epidemiological model (SEIRS+) to simulate SARS-CoV-2 transmission in schools with various mitigation strategies.

Requirements for disease control in primary schools differ from those in secondary schools because the dynamics of SARS-CoV-2 transmission differ among children and adolescents.

Student cohorting, in which students are divided into two separate populations that attend in-person classes on alternating schedules, can reduce both the likelihood and the size of outbreaks.

Proactive testing of teachers and staff once or twice a week can help catch introductions early, before they spread widely through the school. Especially in secondary schools, once- or twice-weekly testing amongst students should also be considered to further reduce the likelihood of a large outbreak amongst the full population.

Quarantining classrooms with an infected student or teacher can further mitigation efforts, particularly when proactive testing is deployed at a high cadence.

Vaccinating teachers and staff may have a disproportionate protective effect on the outbreak potential in primary and secondary schools, if the vaccine can block SARS-CoV-2 transmission with high effectiveness.

Other mitigation strategies — including mask-wearing, social distancing, and increased ventilation — remain a crucial component of any reopening plan.

Introduction

As the COVID-19 pandemic spread, schools across the world closed preemptively in an effort to reduce transmission and protect their students, teachers, and staff. By mid-April of 2020, 195 countries had closed their schools in response to COVID-19, affecting more than 1.5 billion students.[1] In the United States (US), schools were among the first organizations to close, and many remained closed through the end of the 2019-20 school year or transitioned to remote learning.

While remote learning affords students the opportunity to continue their education, it fails to provide many of the crucial benefits students typically receive through in-person learning. A recent report from the Organisation for Economic Co-operation and Development estimates that learning losses from school closures could have lasting impacts for students, equating to a 3% lower income over their lifetime.[2] The United Nations Children's Fund (UNICEF) recently issued a comprehensive six-point plan for keeping schools open, which stressed the need to take immediate action to safeguard the future health and well-being of millions of children.[3] Professional societies, including the National Academies of Sciences, Engineering, and Medicine and the American Academy of Pediatrics, have strongly advocated for the return to in-person learning, while also stressing the importance of using a multi-layer approach to protect students, teachers, and staff from COVID-19 risk.[4,5]

To date, limited data about COVID-19 in schools as well as conflicting public health guidance has made reopening schools a difficult undertaking. There is an urgent need to evaluate the effectiveness of evidence-based strategies that would allow children, teachers, and staff to return to in-person learning.

To better understand the risks associated with reopening schools and returning to in-person learning, we developed an epidemiological model to simulate the spread of SARS-CoV-2 amongst students, teachers, and staff in primary and secondary schools. We use the model to explore the effectiveness of different mitigation strategies, including student cohorting, quarantine protocols, proactive testing, and vaccination.

The purpose of this model is to provide a scenario-simulating tool that, when used in concert along with other credible sources of information and data, can aid policymakers and administrators in their decisions around school reopening policies. Like all epidemiological models, ours is a simplification of a complex, highly variable world, and it is only as good as the assumptions upon which it is built. To the degree that those assumptions do not accurately reflect the epidemiological dynamics or social structure on the ground, the model will be ineffective at predicting even the range of possible outcomes. In a novel pandemic where many epidemiological parameters remain uncertain, and social and behavioral factors are fluid, some mismatch is inevitable.

Model

Epidemiological models, such as the SEIR model, are frequently used to model the spread of disease in a population. The SEIR model is a standard compartmental model which tracks the proportion of the population in different disease states over time. SEIR models include compartments for susceptible (S), exposed (E), infectious (I), and recovered (R) individuals. Over time, individuals within the population move between these states at rates determined by the disease parameters. A susceptible member of the population becomes infected (exposed) when making a transmissive contact with an infectious individual and then progresses to the infectious and eventually recovered states.

Standard compartment models capture important features of infectious disease dynamics, but they are deterministic mean-field models that assume uniform mixing of the population (i.e., every individual in the population is equally likely to interact with every other individual). However, it is often important to consider stochasticity, heterogeneity, and the structure of contact networks when studying disease transmission, and many strategies for mitigating spread can be thought of as perturbing the contact network (e.g., social distancing) or making use of it (e.g., contact tracing).

Here, we use the SEIRS+ model framework developed by Ryan McGee and Carl Bergstrom at the University of Washington. This framework extends the classic SEIR model of infectious disease to represent pre-symptomatic, asymptomatic, and isolated disease states, which are of particular relevance to the COVID-19 pandemic. This framework also supports the implementation of extended SEIR models on stochastic dynamical networks. Individuals are represented as nodes in a contact network, and parameters, interactions, and interventions can be specified on a targeted individual basis. This allows us to model realistic heterogeneity in disease and transmission parameters, interaction patterns, and application of interventions explicitly. Further information and code for the SEIRS+ model framework can be found at https://github.com/ryansmcgee/seirsplus.

The specific model considerations are further described on the next page.

Primary schools versus secondary schools

The dynamics of COVID-19 transmission differ substantially between primary schools and secondary schools for two principal reasons: (1) children (under age 10) and adolescents (ages 10-19) appear to have different epidemiological characteristics of infection, and (2) primary and secondary schools have different organizational structures. A recent meta-analysis showed that younger children have lower susceptibility to SARS-CoV-2 infection and are about half as likely to become infected compared to adults.[6] Younger children are also more likely to experience asymptomatic or mild disease than adults are.[7,8] Organizationally, primary schools are structured into more stable cohorts, with groups of students assigned to a single teacher for the entire day. In contrast, secondary school students typically move from classroom to classroom and thus encounter multiple teachers and groups of students over the course of a single day.

Primary schools also appear to have a lower risk of transmission compared to secondary schools.[9-11] For example, in Israel, all schools were shut down again shortly after reopening because of a large outbreak in a secondary school, however, no cases were reported in primary schools.[10] In New York, between Aug. 31 and Nov. 22, 2020, the case rate for students in primary schools was substantially lower than the case rate reported in teachers and staff and the surrounding community (7.0 vs 19.0 vs 15.0 daily cases per 100,000, respectively).[12] In comparison, during this same time period, the student case rate in high schools was almost double the case rate found in primary students (13.0 vs 7.0 daily cases per 100,000, respectively) and was similar to the case rates reported in teachers and staff and the surrounding community (16.0 vs 15.0 daily cases per 100,000, respectively).[12] While such reports are merely individual snapshots from a widespread and ongoing pandemic, these trends support the notion that transmission occurs less frequently in primary school students compared to those in secondary schools and the surrounding community.

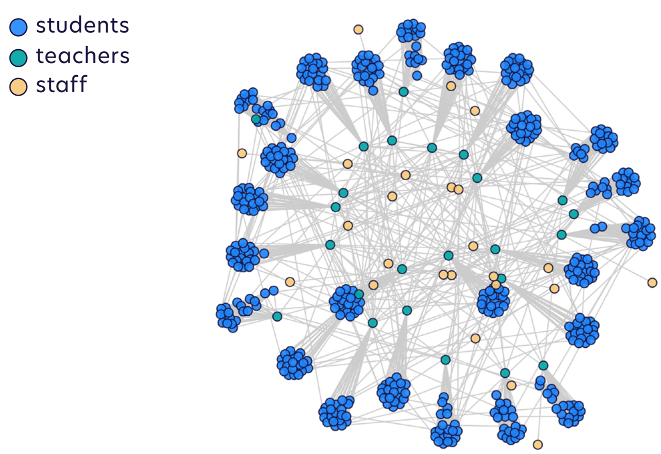
To account for this, we developed two distinct models for primary and secondary schools, each with parameters chosen to reflect these critical differences.

Model network structure

The SEIRS+ model network extends the classic SEIR epidemiological model by adding additional compartments to track presymptomatic, asymptomatic, and symptomatic individuals as well as the ability to incorporate transmission along a contact network. In the SEIRS+ framework, the contact network defines the set of close contacts for each individual in the population. Close contacts are individuals with whom one has non-cursory (e.g., repeated, sustained, and/or close proximity) interactions on a regular basis, such as classmates, friends, housemates, or other close relationships. In contrast, casual contacts are individuals with whom one has incidental, brief, or superficial contact on an infrequent basis and are not connected with the individual in the network. Disease transmission may occur either from close contacts along the network structure or from casual contacts. The network locality parameter *p* sets the relative frequency and weight of transmission among close (local network) and casual (global) contacts in the model population. In both primary and secondary school settings, we assume that 80% of transmission occurs between close contacts specified by the networks. Detailed descriptions of the schools contact structures used in our model can be found in the appendix (Appendix A).

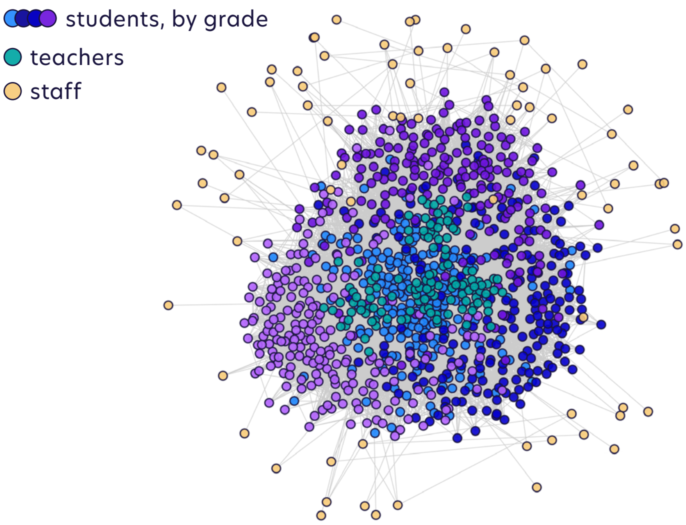
For our primary school model, we simulate a medium-sized school with 480 students, 24 teachers, and 24 additional staff (Figure 1).

Figure 1. Network structure of primary schools. Each individual is represented by a circle, and grey lines represent connections. Students are in blue and organized into classes, teachers are in green, and staff are in yellow.



For our secondary school model, we simulate a medium-sized school with 800 students (200 per graduating class), 125 teachers, and 75 additional staff (Figure 2).

Figure 2. Network structure of secondary schools. Each individual is represented by a circle, and grey lines represent connections. Students are in blues and purples, colored by each of the four grades in the secondary school model, while teachers are in green, and staff are in yellow.



Community prevalence and mitigation strategies

The US Centers for Disease Control and Prevention (CDC) has issued guidance for mitigating the risk of reopening and operating schools during the COVID-19 pandemic.[13] For both primary and secondary schools, the risk of an outbreak increases as community transmission rises. Thus, every effort should be made to maintain low levels of community transmission as schools reopen for in-person learning. The CDC has also developed a set of core indicators to assess the feasibility of reopening schools, which includes transmission levels in the community and the ability to implement mitigation strategies (Table 1).[13] Schools may choose to utilize testing strategies in conjunction with behavioral mitigation strategies, such as masks and social distancing, operational strategies, and environmental controls, to reduce the risk of outbreaks.[14]

Finally, in the event that an outbreak does occur at a school, the CDC recommends that school administrators should work closely with local public health officials to scale testing in order to quickly identify and isolate cases.

Table 1. Summary of the US CDC's recommended mitigation strategies and core indicators for K-12th grade schools

Measures of community prevalence
• The number of new cases per 100,000 persons within the last 14 days AND/OR
• The percentage of RT-PCR tests that were positive during the last 14 days
Key mitigation strategies
• Consistent and correct use of masks and face coverings
• Social distancing
• Hand hygiene and respiratory etiquette
• Cleaning and disinfection of surfaces
• Contact tracing in collaboration with local health department
Additional mitigation strategies
• Alternating or staggered class scheduling
• Cohorting of students
• Proactive testing (screening) of teachers, staff, and/or students
• Ventilation and increased circulation of outdoor air

Simulations

Our model is stochastic, and its outcomes are probabilistic. To account for variability of possible outcomes, we run 1,000 replicates for each parameter set. Simulations last a total of 150 days, representing a full semester of schooling.

We display the simulation results as jitter plots, in which each replicate is depicted as a single point. The collection of all points in the plot represent the distribution of potential outcomes for each simulation parameter set. Under each jitter plot we display the fraction of simulation runs that result in sizable outbreaks, with more than 5% of the population infected over the course of the semester.

Results

Community prevalence

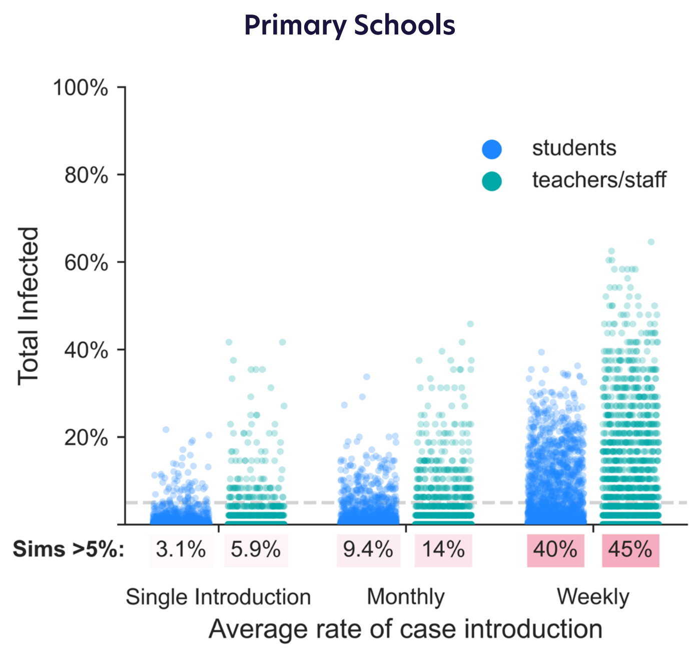
The prevalence of COVID-19 in the community is a critical driver of school-related transmission. To determine how community prevalence impacts the infection rates in schools, we model scenarios in which new cases are randomly introduced into a school population on an approximately weekly, monthly, or once-per-semester basis (Table 2). We note that in the single introduction scenario, all replicates start off with the case introduction occurring on the first day of the model.

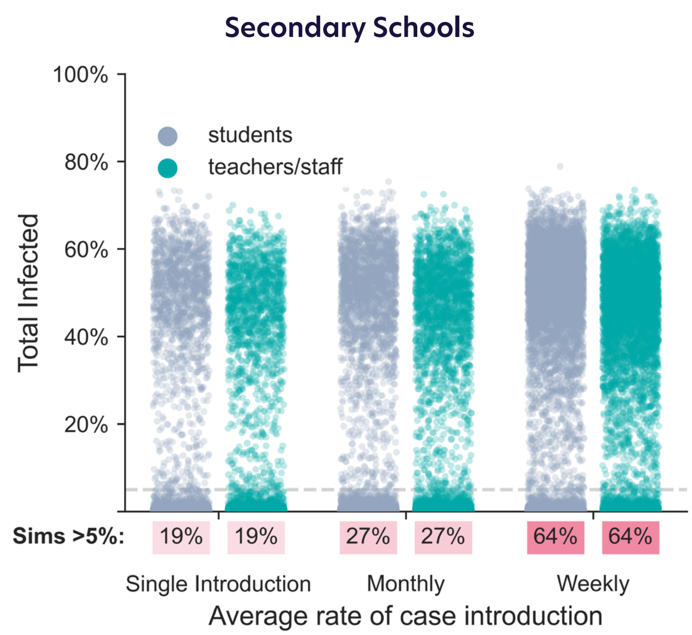
Table 2. Community prevalence model parameters

Average number of new cases introduced in model	Estimated community case prevalence (range)
Single introduction	N/A
One case per month	0.01 - 0.03%
One case per week	0.05 - 0.20%

Figure 3 shows the percentage of the school population infected in primary and secondary schools over the course of a semester. Because chance plays an important role in whether outbreaks occur and how big they become, there are a range of possible outcomes for any given school scenario. To get a sense of this range, we display results from 1,000 stochastic simulations for each condition. Each simulation run has a slightly different outcome, which we indicate with a point on the jitter plots.

Figure 3. Community prevalence. The distributions of model outcomes for students, teachers, and staff in (top) primary schools (size = 528) and (bottom) secondary schools (size = 1,000) over 1,000 simulations under different average rates of new case introductions. Under each jitter plot we list the percentage of simulations that result in outbreaks affecting more than 5% of the population.





Under each jitter plot we list the percentage of simulation runs that lead to outbreaks with more than 5% of the population infected over the course of the semester. In Figure 3 these percentages reveal that as the community prevalence of COVID-19 increases, the probability that a school suffers one or more outbreaks (> 5% infected) increases as well. This is true for both primary and secondary schools.

In primary schools, the jitter plot bars rise higher when introductions are more frequent. This indicates that a larger fraction of the school population can become infected when the community prevalence is higher. In secondary schools, large outbreaks are possible even with a single introduction. But monthly, and particularly weekly, introductions result in a higher density of points representing more simulations in which high fractions of the population are infected. In other words, we are increasingly likely to see large numbers of infected individuals in schools as COVID-19 cases become more common in the community.

Student cohorting

Cohorting, wherein students are divided into two or more groups, is a common strategy for outbreak mitigation. Alternating or staggered scheduling can be used in conjunction with cohorting to further reduce the risk of outbreaks in schools. Using these strategies, only one cohort of students from each class is on campus at any given time, and teachers work with all cohorts in succession. In Figure 4 we model three common cohorting strategies: (1) students divided into two cohorts (A and B) which are on campus on alternating days, (2) students divided into two cohorts (A and B) which are on-campus on alternating weeks, and (3) all students belong to a single class cohort that is on-campus full time (five days a week). Network structures for student cohorting are shown in Figure 5. In all strategies, students are disconnected from the school network but maintain global transmission while off campus (the latter representing out-of-school interactions among students). We find that the use of a student cohorting strategy, in conjunction with alternating schedules, greatly improves both metrics compared to no cohorting at all (Figure 4). with approximately weekly new case introductions and no testing

Figure 4. School Cohorting Strategies. The distribution of model outcomes among 1,000 simulations for three different cohorting strategies in (top) primary schools and (bottom) secondary schools with approximately weekly new case introductions and no testing. Under each jitter plot we list the percentage of simulations that result in outbreaks affecting more than 5% of the population.

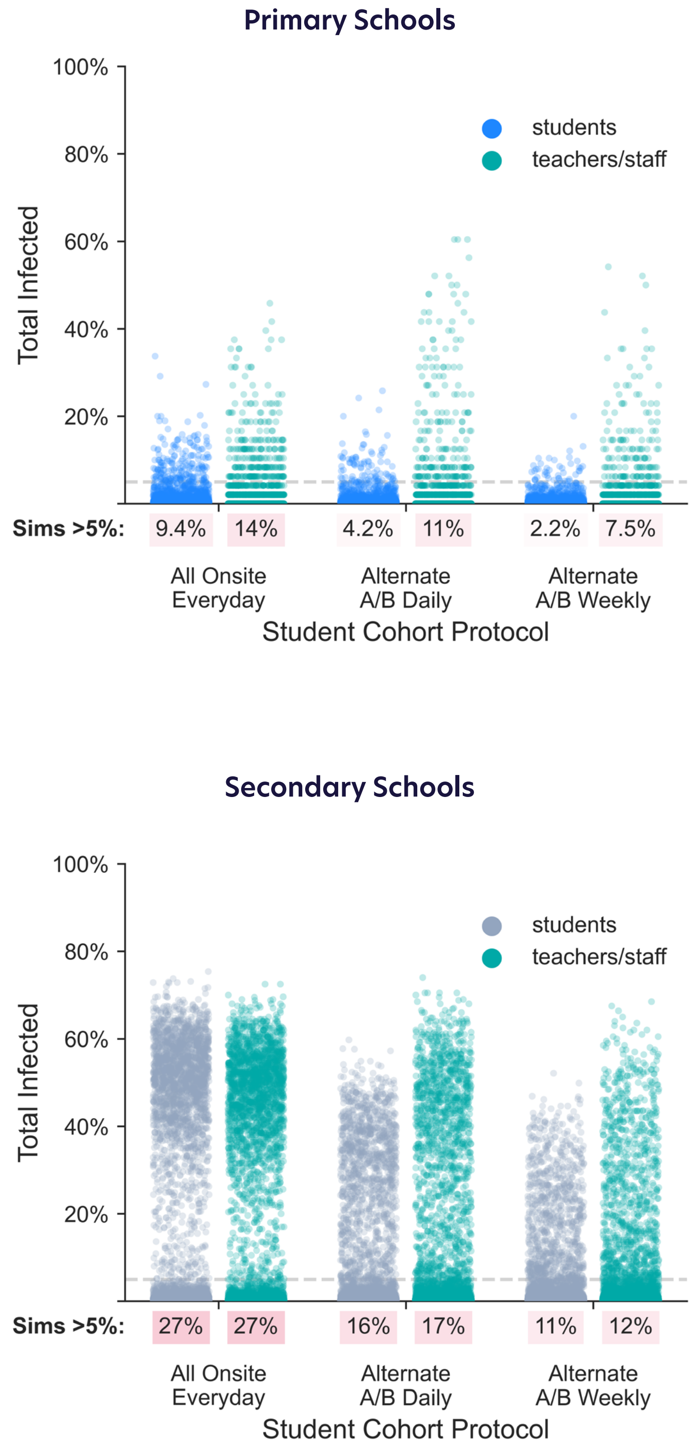
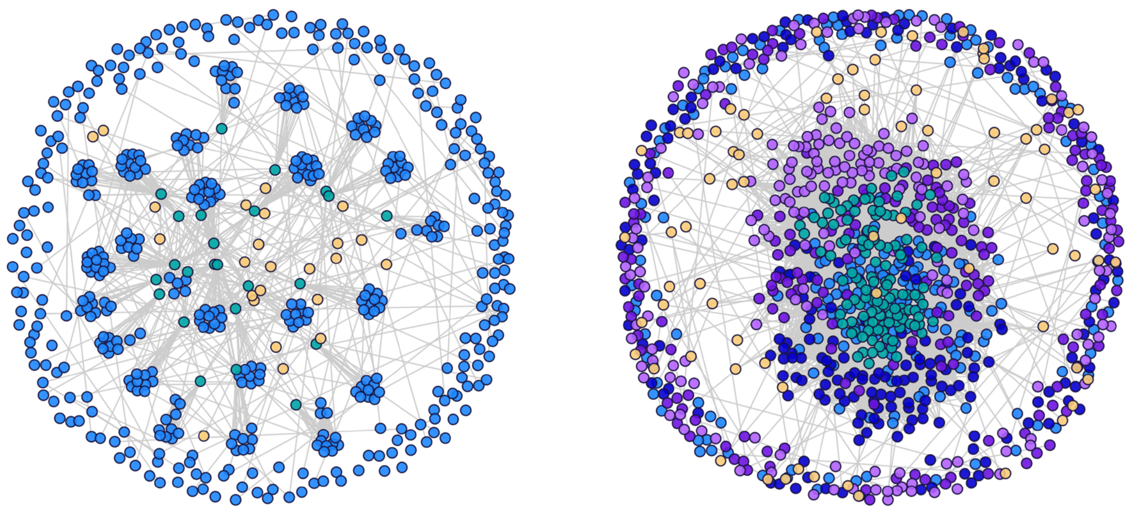


Figure 5. Network structures for student cohorting. Modified network structures used to simulate student cohorting into two groups (A and B) are shown when the A cohorts are at school and the B cohorts are at home. In the primary school network (left), students in the A cohort are arranged into small classes represented by the tight clusters in the interior. Students in the B cohort are not in school and appear around the periphery of the network diagram. In the secondary school network (right), students in the A cohort are attending classes and appear in the interior, and students in the B cohort are at home and ring the periphery. Students are indicated in blues and purples and colored by grade in the secondary school network, while teachers are in green, and staff are in yellow.



In primary schools, A and B cohorting alone reduces the risk of outbreak amongst students. In the secondary school population, A and B cohorting — while helpful — is insufficient to keep the likelihood of an outbreak low amongst students or teachers and staff.

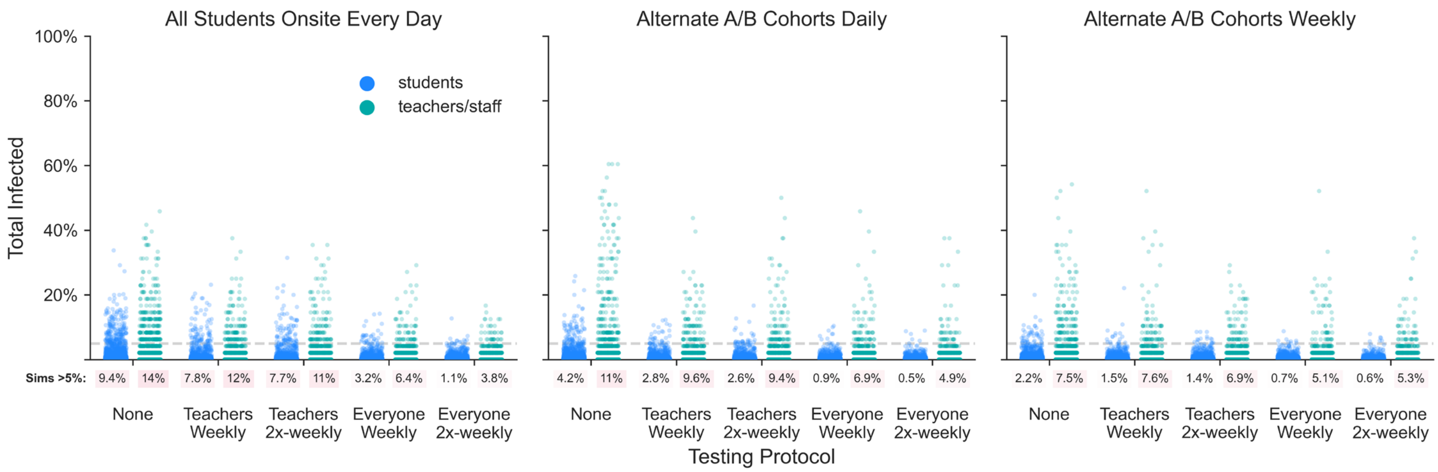
Proactive testing

Proactive testing is a powerful control measure that can be used to prevent a potential SARS-CoV-2 outbreak in congregate settings.[15] The purpose of proactive testing is to (1) identify individuals who are infected but not currently showing symptoms and (2) isolate these individuals before they infect others. Based on our previous work in modeling proactive testing for workplaces,[16] we developed a similar framework for schools.

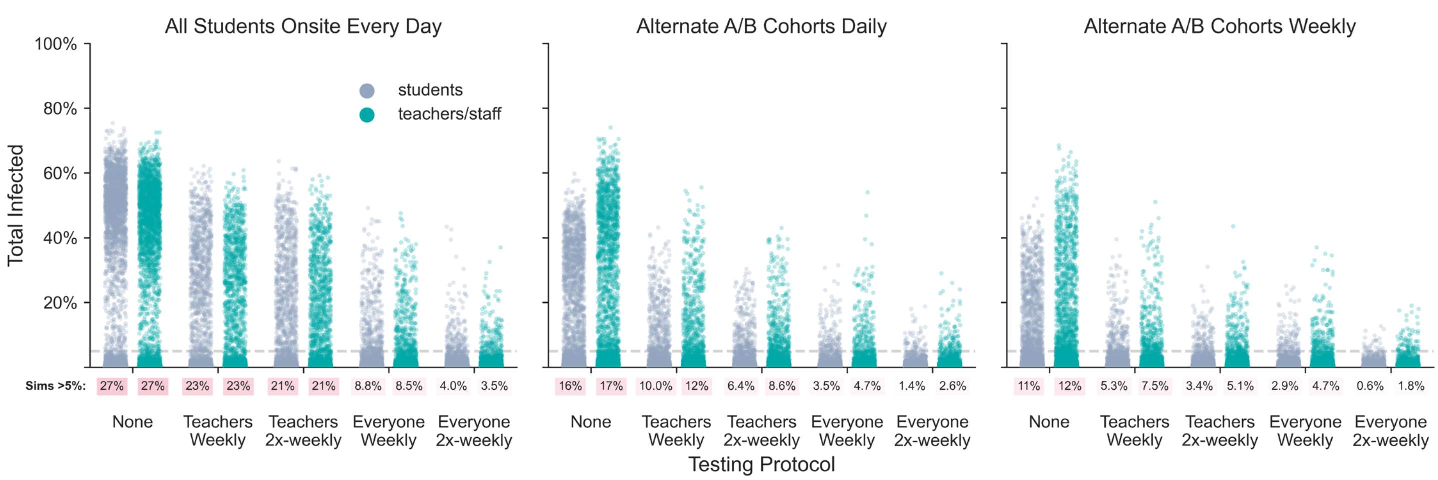
To evaluate the impact that proactive testing and subsequent quarantine would have on the size and frequency of SARS-CoV-2 outbreaks in primary and secondary school settings, we consider five testing strategies: **(1)** twice-weekly proactive testing amongst teachers and staff only, **(2)** once-weekly proactive testing amongst teachers and staff only, **(3)** twice-weekly proactive testing amongst students, teachers, and staff, **(4)** once-weekly proactive testing cadence amongst students, teachers, and staff, and **(5)** no testing. We use a one day turn around time for test results in all replicates. Overall, the model predicts that proactive testing strategies improve outcomes (Figure 6).

Figure 6. Proactive testing strategies. The distribution of model outcomes given different proactive testing strategies and cohorting strategies in (top) primary schools and (bottom) secondary schools with approximately weekly new case introductions and no testing. Under each jitter plot we list the percentage of simulations that result in outbreaks affecting more than 5% of the population.

Primary Schools



Secondary Schools



In the primary school scenarios, our model suggests that proactive testing of teachers and staff, when used in conjunction with A and B cohorting, can mitigate potential outbreaks. Expanding proactive testing to include students further reduces the number of cases among students and teachers alike (Figure 6, top panel).

In the secondary school scenarios, our model demonstrates that proactively testing the entire school population plays an important role in mitigating outbreaks, even with the use of an A and B cohorting strategy (Figure 6, bottom panel). Compared to primary schools, the secondary school scenarios in our model are more prone to outbreaks in which greater than 5% of the total population becomes infected. As such, stronger mitigation measures may be necessary to reopen secondary education.

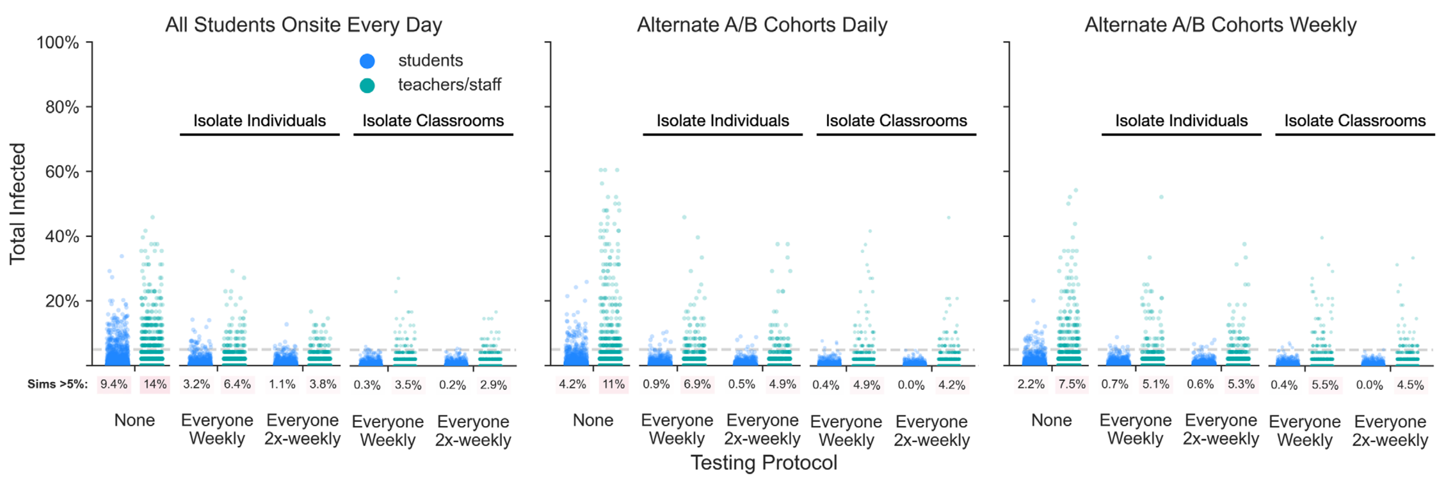
Quarantine Protocols

When an infected individual is identified by proactive testing, that person should be isolated to prevent further transmission. In primary schools where cohorts are stable, school administrators may consider quarantining the entire classroom with which that individual was associated.

Our model indicates that classroom-level quarantine is more effective than individual quarantine when the testing cadence is higher (Figure 7). In addition, this strategy is also more useful when case prevalence in the community is higher as well.

Figure 7. Quarantine protocol strategies. The distribution of model outcomes over 1,000 simulations when using different quarantine and testing strategies in primary schools with approximately weekly new case introductions. Under each jitter plot we list the percentage of simulations that result in outbreaks affecting more than 5% of the population.

Primary Schools



Vaccination

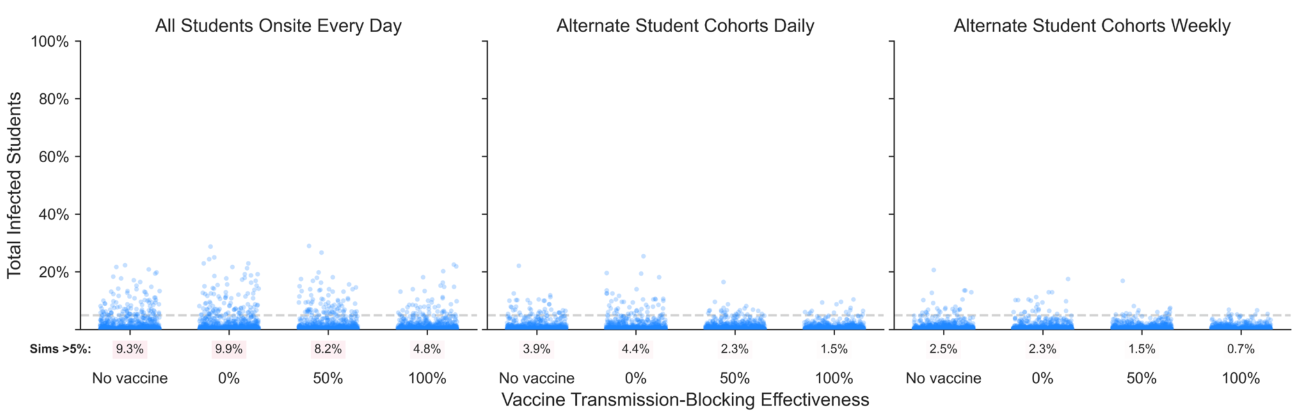
Pfizer-BioNTech and Moderna have reported extremely encouraging results from their phase III clinical trials, with 90% or greater efficacy at blocking symptomatic disease. Distribution of the Pfizer-BioNTech vaccine is underway in the US, with Moderna's vaccine expected to follow shortly. Other vaccines may also be close behind in the pipeline. Guidance from the US Advisory Committee on Immunization Practices has recommended that first available doses of the vaccine be distributed to healthcare personnel and residents in long-term care facilities.[17] As more vaccine doses become available, it is likely that vaccination programs will be expanded to essential workers, including school teachers and staff.

A recent UNICEF statement urged that teachers be prioritized for vaccination (after frontline workers) to help protect them from infection and to allow schools to reopen for in-person learning.[18]

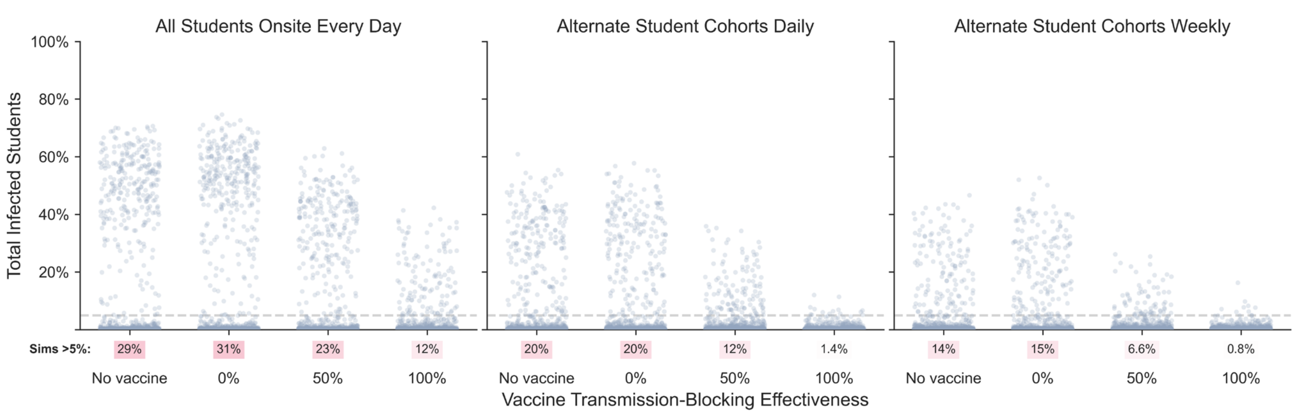
Some vaccines, such as those for measles, may block infection, disease, and transmission. Others, such as the pneumococcal (bacterial pneumonia) conjugate vaccine and the acellular pertussis (whooping cough) vaccine, may have a smaller effect on infection and transmission. Because all COVID-19 vaccine trial data to date have focused only on diagnosis of symptomatic disease as a primary endpoint, we do not know the degree to which COVID-19 vaccines block transmission. As such, we include multiple scenarios for post-vaccination transmissibility in the model (Figure 8).

Figure 8. Effect of vaccination. The distribution of model outcomes for students when no teachers and staff are vaccinated compared to when all teachers and staff are vaccinated with varying transmission-blocking effectiveness. Results are shown for (top) primary schools and (bottom) secondary schools with approximately weekly new case introductions and no testing. Under each jitter plot we list the percentage of simulations that result in outbreaks affecting more than 5% of the student population.

Primary Schools



Secondary Schools



Our model predicts that when teachers and staff are given a COVID-19 vaccine with 90% effectiveness, the likelihood of outbreaks will be greatly reduced in primary and secondary school settings alike — assuming that the vaccine is able to block transmissibility entirely. In the secondary school model, the inclusion of transmission-blocking vaccinations for teachers and staff dramatically decreases the number of simulations that result in COVID-19 infections in more than 5% of the total population.

Vaccine effects are substantially less striking if the vaccine only partially reduces transmissibility. Nonetheless, even a vaccine with limited ability to block transmission confers an important protective effect on the teacher and staff population (Figure 8).

Conclusion

Here, we have presented results from a simulation model of reopening schools during the COVID-19 pandemic. It is important to note that chance plays a big role in outbreaks; two schools with very similar characteristics and mitigation plans may experience substantially different outcomes. We attempt to capture this with the stochastic nature of our model. For each scenario we illustrate the range of likely outcomes, rather than predicting a specific result.

Additional uncertainty arises in the form of epidemiological parameters that remain unknown, and through unpredictable and dynamically changing aspects of human behavior. We attempt to make the most reasonable assumptions about both of these domains. To the degree that our assumptions are off, the model's predictions will be inexact. Even where this happens, the qualitative predictions of a well-structured model are often robust to misestimation of parameters, and the general trends that we observe here — advantages to cohorting, testing, and vaccination — are likely to hold up more broadly.

Schools that plan to reopen for in-person learning must implement outbreak mitigation measures. Diligent use of masks, social distancing, and other environmental controls remain critical to reduce the risk of transmission within schools. Our model's results demonstrate that in addition to these environmental and behavioral controls, cohorting students, proactively testing some or all of the school population, and vaccinating teachers can further reduce the risk of outbreaks in schools.

Dividing up students into two stable cohorts that attend school in-person on alternating schedules can be an effective outbreak mitigation strategy. Due to the more stable classroom organization of primary schools, student cohorting is a more effective strategy there than in secondary schools. Given the potential utility of this strategy, secondary schools could consider restructuring classroom organizations to mimic the stable cohorts of primary schools to increase the effectiveness of cohorting. Note that student cohorting is effective in our model because students largely restrict in-person interactions to other individuals within their groups, and this takes place only while at school. Intermingling or socializing of student cohorts outside of school must be minimized to achieve the maximal protective effect of cohorting.

Compared to students, teachers and staff are at higher risk for more severe disease and, in primary schools, pose a higher risk of spreading the virus. Moreover, primary school teachers serve as conduits for outbreaks to move among classrooms within the school network. Frequent, proactive testing of teachers and staff can interrupt such transmission chains and further protect them from infection.

Vaccinating teachers and staff is a powerful tool for protecting this critical workforce. In addition, if vaccines prove to effectively block SARS-CoV-2 transmission in addition to COVID-19 symptoms, vaccinating teachers and staff can dampen outbreak dynamics in both primary and secondary schools. The result would be fewer cases among adults and students alike. These factors merit consideration when determining the priority, as well as the requirement, for teachers and staff to be vaccinated before returning to school.

While there are still gaps in our understanding of transmission in school settings, both real-world experience and models — including the one presented here — suggest that there is a path for schools to reopen for in-person learning, particularly when community transmission is low and mitigation measures are deployed and consistently implemented.

Appendix

A Schools contact structures

For our primary school model, we simulate a medium-sized school of 480 students with 24 teachers and 24 additional staff. Each class comprises one teacher and 20 students in mutual contact. Additionally, each teacher interacts with a handful of other teachers and staff, and students that share the same household (as calibrated by US census data) are connected. Most of the contacts that an individual makes in the school population are with the students and teacher in their own class, and disease transmission within a class is more likely than between classes (Figure 1).

For our secondary school model, we consider both (a) a medium-sized school with 800 students (200 per graduating grade), 125 teachers, and 75 staff, and (b) a large school with 2,000 students (500 per graduating grade), 175 teachers, and 75 staff.

We define network layers for students and teachers and staff using the FARZ network generation algorithm, which allows us to calibrate epidemiologically-important network properties (e.g., community structure, assortativity, and clustering coefficient) to values consistent with studies of secondary school contact networks. A FARZ community network layer is generated for each grade, with students belonging to one or more social groups of about 10 individuals. 80% of each student's contacts are with students in the same grade, and 80% of those within-grade contacts are with students in their own social groups. Students that share a household (as calibrated by US census data) are connected as well. Interactions between teachers and staff are represented by another FARZ network layer with a total of six communities. Finally, students are connected with six random teachers with whom they have classes, with students in the same grade being more likely to share teachers (Figure 2).

Table A.1 Model parameters and values for SARS-CoV-2

Parameter	Mean Value	Description
R_0	2.0	The R_0, or reproductive number, is the expected average number of secondary infectious cases produced by a single infectious case. This level of baseline transmissibility (R_0=2.0) assumes that basic mitigation strategies, such as mask-wearing and social distancing, are in place.
Student Susceptibility	60% for primary school students, 100% for secondary school students	Children 10 and younger are less susceptible to infection than older children and adults.
Latent period	3.0 days[21-24]	The time from exposure to when the individual becomes infectious to others.
Presymptomatic infectious period	2.2 days[19,20]	The period when an individual infected with SARS-CoV-2 is contagious but has not yet developed symptoms.
Infectious period	6.2 days[20,25-27]	The time period during which an infected individual is infectious to others. For symptomatic cases, this includes the presymptomatic period.
Test sensitivity	75% while presymptomatic, 90% during first 3 days of infectious period, and decreasing thereafter[28,29]	Probability that a single test will correctly identify an infectious individual as having SARS-CoV-2.
Testing Compliance	100% for teachers and staff, 75% for students	Probability that an individual will comply with the testing protocol, if any.
Percent asymptomatic	30% for adults and secondary school students, 40% for primary school students [30-33]	Percentage of individuals infected with SARS-CoV-2 who do not develop symptoms.
Percent symptomatic who self-quarantine	20%	Percentage of symptomatic individuals who develop sufficient symptoms (e.g., fever) that they call in sick and stay home from work or school.
Test turnaround time	1 day	Length of time between testing and isolation for individuals who receive positive results.
Isolation Time	10 days[34,35]	Isolation time for individuals who receive a positive test result, self-isolate due to symptoms, or quarantine in response to a known positive contact.
Vaccine Efficacy	90%	Percentage of vaccinated individuals in which the vaccine takes effect.

Table A.2 Model assumptions for (left) primary schools and (right) secondary schools

Primary School Structure	
Age of students (range)	5 to 10 years
Number of grades	6 (Kindergarten through 5th)
Classes per grade	4
Students per class (teacher)	20
Number of students	480 (#grades x #classes/grade x #students/class)
Number of teachers	24 (#grades x #classes/grade x 1)
Number of staff	24
Student-student connections	Well-connected within classroom; Household (siblings) connected

Secondary School Structure	
Age of students (range)	3 to 18 years
Number of grades	4 (9th through 12th)
Students per grade	200 (medium schools), 500 (large schools)
Number of teachers	125 (medium schools), 175 (large schools)
Number of staff	75
Student-student connections	Connected to 16 other students on average; Household (siblings) connected
Teacher-staff connections	Connected to 10 other teachers/staff on average
Student-teacher connections	Each student connects to 6 teachers

References

1. 1.3 billion learners are still affected by school or university closures, as educational institutions start reopening around the world, says UNESCO. Published April 29, 2020. Accessed November 9, 2020. https://en.unesco.org/news/13-billion-learners-are-still-affected-school-university-closures-educational-institutions

2. Hanushek EA, Woessmann L. The economic impacts of learning losses. Published online 2020. https://www.oecd-ilibrary.org/education/the-economic-impacts-of-learning-losses_21908d74-en

3. Averting a lost COVID generation. Accessed December 10, 2020. https://www.unicef.org/reports/averting-lost-generation-covid19-world-childrens-day-2020-brief

4. American Academy of Pediatrics, Others. COVID-19 planning considerations: guidance for school re-entry. *Critical Updates on COVID-19-Clinical Guidance*. 2020;2019:1-11.

5. National Academies of Sciences, Engineering, and Medicine; Division of Behavioral and Social Sciences and Education; Board on Children, Youth, and Families; Board on Science Education; Standing Committee on Emerging Infectious Diseases and 21st Century Health Threats; Committee on Guidance for K-12 Education on Responding to COVID-19. *Reopening K-12 Schools During the COVID-19 Pandemic: Prioritizing Health, Equity, and Communities.* (Schweingruber H, Dibner K, Bond EC, eds.). National Academies Press (US); 2020.

6. Viner RM, Mytton OT, Bonell C, et al. Susceptibility to SARS-CoV-2 Infection Among Children and Adolescents Compared With Adults: A Systematic Review and Meta-analysis. *JAMA Pediatr.* Published online September 25, 2020. doi:10.1001/jamapediatrics.2020.4573

7. Assaker R, Colas A-E, Julien-Marsollier F, et al. Presenting symptoms of COVID-19 in children: a meta-analysis of published studies. *Br J Anaesth.* 2020;125(3):e330-e332.

8. Rajmil L. Role of children in the transmission of the COVID-19 pandemic: a rapid scoping review. *BMJ Paediatr Open.* 2020;4(1):e000722.

9. Goldstein E, Lipsitch M, Cevik M. On the effect of age on the transmission of SARS-CoV-2 in households, schools and the community. *J Infect Dis.* Published online October 29, 2020. doi:10.1093/infdis/jiaa691

10. Stein-Zamir C, Abramson N, Shoob H, et al. A large COVID-19 outbreak in a high school 10 days after schools' reopening, Israel, May 2020. *Eurosurveillance.* 2020;25(29):2001352.

11. Ismail SA, Saliba V, Bernal JL, Ramsay ME, Ladhani SN. SARS-CoV-2 infection and transmission in educational settings: a prospective, cross-sectional analysis of infection clusters and outbreaks in England. *The Lancet Infectious Diseases.* Published online 2020. doi:10.1016/s1473-3099(20)30882-3

12. XM_DASHBOARD. Accessed December 11, 2020. https://statsiq.co1.qualtrics.com/public-dashboard/v0/dashboard/5f78e5d4de521a001036f78e#/dashboard/5f78e5d4de521a001036f78e?pageId=Page_c0595a5e-9e70-4df2-ab0c-14860e84d36a

13. Centers for Disease Control. Communities, Schools, Workplaces, & Events. Published December 3, 2020. Accessed December 11, 2020. https://www.cdc.gov/coronavirus/2019-ncov/community/schools-childcare/index.html

14. Centers for Disease Control. Interim Considerations for Testing for K-12 School Administrators and Public Health Officials. Published December 4, 2020. Accessed December 15, 2020. https://www.cdc.gov/coronavirus/2019-ncov/community/schools-childcare/k-12-testing.html

15. Black JRM, Bailey C, Przewrocka J, Dijkstra KK, Swanton C. COVID-19: the case for health-care worker screening to prevent hospital transmission. *Lancet.* 2020;395(10234):1418-1420.

16. Color. Explore the impact of proactive testing on SARS-CoV-2 outbreaks - Color. Color Outbreak Modelling Tool. Published July 25, 2020. Accessed December 16, 2020. https://www.color.com/covid-19-outbreak-model

17. Dooling K. The Advisory Committee on Immunization Practices' Interim Recommendation for Allocating Initial Supplies of COVID-19 Vaccine — United States, 2020. *MMWR Morb Mortal Wkly Rep.* 2020;69. doi:10.15585/mmwr.mm6949e1

18. Teachers should be prioritized for vaccination against COVID-19. Accessed December 15, 2020. https://www.unicef.org/press-releases/teachers-should-be-prioritized-vaccination-against-covid-19

19. Tindale L, Coombe M, Stockdale JE, et al. Transmission interval estimates suggest pre-symptomatic spread of COVID-19. *Epidemiology.* Published online March 6, 2020. doi:10.1101/2020.03.03.20029983

20. He X, Lau EHY, Wu P, et al. Temporal dynamics in viral shedding and transmissibility of COVID-19. *Nat Med.* 2020;26(5):672-675.

21. Li Q, Guan X, Wu P, et al. Early Transmission Dynamics in Wuhan, China, of Novel Coronavirus-Infected Pneumonia. *N Engl J Med.* 2020;382(13):1199-1207.

22. Lauer SA, Grantz KH, Bi Q, et al. The Incubation Period of Coronavirus Disease 2019 (COVID-19) From Publicly Reported Confirmed Cases: Estimation and Application. *Ann Intern Med.* 2020;172(9):577-582.

23. Guan W-J, Ni Z-Y, Hu Y, et al. Clinical Characteristics o f Coronavirus Disease 2019 in China. *N Engl J Med.* 2020; 382(18):1708-1720.

24. Backer JA, Klinkenberg D, Wallinga J. Incubation period of 2019 novel coronavirus (2019-nCoV) infections among travellers from Wuhan, China, 20-28 January 2020. *Euro Surveill.* 2020;25(5). doi:10.2807/1560-7917.ES.2020.25.5.2000062

25. Wölfel R, Corman VM, Guggemos W, et al. Virological assessment of hospitalized patients with COVID-2019. *Nature.* 2020;581(7809):465-469.

26. Ganyani T, Kremer C, Chen D, et al. Estimating the generation interval for coronavirus disease (COVID-19) based on symptom onset data, March 2020. *Euro Surveill.* 2020;25(17). doi:10.2807/1560-7917.ES.2020.25.17.2000257

27. Young BE, Ong SWX, Kalimuddin S, et al. Epidemiologic Features and Clinical Course of Patients Infected With SARS-CoV-2 in Singapore. *JAMA.* Published online March 3, 2020. doi:10.1001/jama.2020.3204

28. Wikramaratna P, Paton RS, Ghafari M, Lourenco J. Estimating false-negative detection rate of SARS-CoV-2 by RT-PCR. *Epidemiology.* Published online April 7, 2020. doi:10.1101/2020.04.05.20053355

29. Kucirka LM, Lauer SA, Laeyendecker O, Boon D, Lessler J. Variation in False-Negative Rate of Reverse Transcriptase Polymerase Chain Reaction-Based SARS-CoV-2 Tests by Time Since Exposure. *Ann Intern Med.* Published online May 13, 2020. doi:10.7326/M20-1495

30. Treibel TA, Manisty C, Burton M, et al. COVID-19: PCR screening of asymptomatic health-care workers at London hospital. *Lancet.* 2020;395(10237):1608-1610.

31. Nishiura H, Kobayashi T, Miyama T, et al. Estimation of the asymptomatic ratio of novel coronavirus infections (COVID-19). *Int J Infect Dis.* 2020;94:154-155.

32. Byambasuren O, Cardona M, Bell K, Clark J, McLaws M-L, Glasziou P. Estimating the extent of true asymptomatic COVID-19 and its potential for community transmission: systematic review and meta-analysis. *medRxiv.* Published online 2020. https://www.medrxiv.org/content/10.1101/2020.05.10.20097543v1.abstract

33. Mizumoto K, Kagaya K, Zarebski A, Chowell G. Estimating the asymptomatic proportion of coronavirus disease 2019 (COVID-19) cases on board the Diamond Princess cruise ship, Yokohama, Japan, 2020. *Euro Surveill.* 2020;25(10). doi:10.2807/1560-7917.ES.2020.25.10.2000180

34. Centers for Disease Control and Prevention. Options to reduce quarantine for contacts of persons with SARS-CoV-2 infection using symptom monitoring and diagnostic testing. Published December 2, 2020. Accessed December 16, 2020. https://www.cdc.gov/coronavirus/2019-ncov/more/scientific-brief-options-to-reduce-quarantine.html

35. Centers for Disease Control and Prevention. Duration of isolation and precautions for adults with COVID-19. Published December 1, 2020. Accessed December 16, 2020. https://www.cdc.gov/coronavirus/2019-ncov/hcp/duration-isolation.html